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THE USE OF CORAL AS AN AGGREGATE FOR PORTLAND CEMENT CONCRETE STRUCTURES

ARMY CONSTRUCTION ENGINEERING RESEARCH LABORATORY

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This investigation documents the experience gained by the Corps of Engineers and the Navy since World War II in the use of coral as an aggregate for portland cement concrete. The approach was to evaluate relevant literature and construction and inspection records, visit construction and material preparation sites, evaluate existing coral concrete structures, and analyze coral aggregate and coral concrete samples in the laboratory.

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The results of the investigation indicate that coral has successfully been used as an aggregate for concrete in vertical construction. The only significant type of deterioration observed in coral concrete structures was the cracking and spalling of concrete associated with corroding reinforcing steel. The severity of the corrosion-spalling problem was sufficient in some cases to affect structural integrity, while in other cases little or no deterioration was observed.

For the most part specifications and construction techniques currently being used for production of coral aggregate and coral concrete are similar to specifications and techniques for conventional aggregate and concrete.

FOREWORD

The investigation was conducted as part of the O & MA Program, Project P728012.14 4DM78012AOK1, "Engineering Criteria for Design and Construction," Task 02, "Applications Engineering," Work Unit 104, "Use of Coral as a Construction Material." The work was performed in the Construction Materials Branch of the Materials Systems and Science Division, Construction Engineering Research Laboratory (CERL), under the direction of the Engineering Division, Directorate of Military Construction, Office of the Chief of Engineers. Mr. Sam Gillespie was Technical Monitor.

CERL personnel actively engaged in the planning, testing, and analysis phases of this study were E. M. Cundiff, R. F. Kemphues, R. Neathammer, and F. T. Abt. Other agencies and personnel actively engaged in the study are listed in Appendix A.

During the investigation Mr. E. A. Lotz was Division Chief. Dr. L. R. Shaffer is Director of CERL.

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THE USE OF CORAL AS AN AGGREGATE FOR PORTLAND CEMENT CONCRETE STRUCTURES

1 INTRODUCTION

Purpose and Scope. The purpose of this investigation was to document the experience gained by the Army Corps of Engineers and the Navy Civil Engineer Corps since World War II in the use of coral as an aggregate for portland cement concrete (PCC). The scope of the investigation was limited to the evaluation of coral concrete vertical construction and structures on the Islands of Guam, Saipan, Kwajalein, and Midway.

Approach. Coral concrete construction techniques, both past and present, were evaluated and related to the integrity of existing coral concrete structures. An attempt was made to determine where coral concrete construction techniques and coral concrete structural performance differed from conventional aggregate concrete. This was accomplished by evaluating relevant literature and construction and inspection records, visiting construction and material preparation sites, evaluating existing coral concrete structures, and collecting coral aggregate and coral concrete samples for laboratory analysis. The laboratory analysis assisted in identification of the parameters that affect coral concrete distress.

Background

Coral. All coral is of marine origin and is scientifically classified as an organic sedimentary rock. It is light in color and ranges from unconsolidated deposits of beach sand to dense reef deposits of consolidated limestone. The dominant material found in coral limestone is calcite. Typical coral consists of 95 to 99 percent calcium carbonate.

Coral is formed by minute marine organisms, coral polyps, and nullipore algae. Coral polyps and algae produce calcareous secretions. These secretions form skeletal remains that become limestone by gradual calcification and recrystallization. Coral growth is normally limited to water temperatures between 64° and 96°F, depths less than 180 ft, and clean circulating sea water.

Coral deposits vary tremendously but are normally defined as either reef, beach, or lagoon. The deposits can exist well above sea level (compacted limestones deposited when the ocean was higher) or as loose or well-cemented deposits near or below sea level. Numerous classification systems have been used to describe coral materials. This variety has caused much confusion and ambiguity. A detailed qualitative description of one recent classification system is found in the glossary.

Coral Concrete. Prior to World War II it was generally assumed that coral was not a suitable aggregate for PCC. But during the war most of the concrete placed at advanced bases on the tropical islands of the Pacific was composed of cement and coral aggregate. This was because no other rock was indigenous to large groups of islands such as the Lines, Gilberts, Marshalls, and Leeward Islands of the Hawaiian Archipelago. Even on the larger islands that contained other rock forms, coral was often used because it was more accessible. The use of coral aggregate in concrete was continued after the war in those areas where other suitable aggregate was not readily accessible. Major post World War II coral concrete construction efforts in the Pacific have occurred on the islands of Midway, Kwajalein, Eniwetok, Bikini, Johnston, Wake, Saipan, and Guam.

Most of the published information on coral concrete has been related to one of the following three coral concrete construction periods: World War II and immediate post-war construction,[1,2,3,4] Atomic Energy Commission construction at Eniwetok and Bikini during the late 1940's and early 1950's,[5] and the Navy's Advanced Early Warning (AEW) construction at Midway during the mid 1950's.[6] The Navy Civil Engineering Laboratory (USN CEL) conducted an extensive laboratory evaluation during the 1950's and early 1960's and

[1]Ben E. Nutter, "The Use of Coral Aggregate," *Proceedings, ACI Journal*, Vol 40 (1944), pp 61-65.

[2]J. R. Perry, "Coral—A Good Aggregate in Concrete," *Engineering News-Record* (August 1945), pp 116-122.

[3]I. S. Rasmusson, "Concrete at Advance Bases," *Proceedings, ACI Journal*, Vol 40 (1944), pp 541-551.

[4]C. Martin Duke, "Engineering Properties of Coral Reef Material," *ASTM Proceedings*, Vol 49 (1949), pp 964-976.

[5]D. Lee Narver, "Good Concrete Made with Coral and Sea Water," *Civil Engineering*, Part I (October 1954), pp 40-44; Part II (November 1954), pp 49-52.

[6]*Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

published a series of reports on coral and its use as a concrete aggregate.[7,8,9,10]

Published information contained criteria for selecting coral aggregate sources for quarrying and processing coral aggregate, and for mix proportioning and mixing coral concrete.[11,12,13,14] Other publications presented information on the durability of coral concrete structures and probable causes for coral concrete distress and deterioration.[15,16,17]

The published material affirms that coral has been used successfully as an aggregate for concrete. It has also been determined that sea or brackish mix water only slightly reduces the ultimate strength of concrete. Conversely, it has been determined that the presence of salt in concrete, regardless of origin, destroys the passivity of embedded steel and leads to corrosion if sufficient water and oxygen are present. This loss of passivity has been observed with salt concentrations as low as 0.2 percent.[18] The problem of corroding steel embedded in concrete is compounded by the fact that the products of corrosion require a greater volume than the uncorroded steel. Thus concrete cracking and spalling is actually a byproduct of reinforcing steel corrosion. The corrosion of reinforcing steel in coral concrete has been documented as a major form of coral concrete deterioration.[19,20]

2 FIELD EVALUATION

Introduction. The field evaluation of this study was limited to the islands of Guam, Saipan, Kwajalein, and Midway. All four islands are located north of the equator in the Pacific (Figure 1). Physically the islands are of two forms: Guam and Saipan are volcanic with much overlying coralline limestone; Kwajalein and Midway are coral atolls. A brief description of island location, extent, physiography and the wide range of climatic conditions is contained in Table 1.

Material Preparation. Material preparation included aggregate acquisition and processing, and concrete batching and mixing. The techniques used on each island were somewhat different and therefore material preparation is discussed on a per island basis. It should be noted that all islands have common problems: remoteness from sources of equipment and repair parts, a tropical marine environment that accelerates construction equipment deterioration, and with the exception of Guam, a limited and fluctuating construction volume.

Guam. Rock material acceptable for aggregate production was abundant on Guam. Compact coralline limestone, the most suitable aggregate material available, was accessible over a large portion of the central part and northern plateau of Guam. It could also be found on outcrops around the perimeter of the island. Volcanic rock (similar to basalt rock) was common but relatively inaccessible. Natural sand and gravel existed only in limited quantities, usually as beach deposits, and were not often used as concrete aggregate.

Two commercial quarries were being operated at Guam during the field evaluation (Figure 2). Located in the east central part of the island, both operations were quarrying coralline limestone and

[7] William R. Lorman, *Characteristics of Coral Aggregate from Selected Locations in the Pacific Ocean Area*, TN-335A (USN Civil Engineering Laboratory [USN CEL], 1958).

[8] William R. Lorman, *Characteristics of Coral Mortars*, TR-041 (USN CEL, 1960).

[9] William R. Lorman, *Coral and Coral Concrete*, TR-068 (USN CEL, 1960).

[10] William R. Lorman, *Permeability of Coral Concrete*, TR-R280 (USN CEL, 1964).

[11] J. R. Perry, "Coral—A Good Aggregate in Concrete," *Engineering News-Record* (August 1945), pp 116-122.

[12] D. Lee Narver, "Good Concrete Made with Coral and Sea Water," *Civil Engineering*, Part I (ASCE, October 1954), pp 40-44.

[13] Lorman, *Coral and Coral Concrete*.

[14] I. S. Rasmusson, "Concrete at Advance Bases," *Proceedings, ACI Journal*, Vol 40 (1944), pp 541-555.

[15] Lorman, *Coral and Coral Concrete*.

[16] *Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

[17] C. H. Scholer, *Examination and Study of Certain Structures in the Pacific Ocean Area*, Progress Report, USNCEL Contract NBy-3171 (USN CEL, June 1959).

[18] D. T. Klodt, "A Study of Prestressing Steel-Effect of Stress, Metallurgical Structure and Environment," *Proceedings of National Association of Corrosion Engineers, 24th Conference* (1968).

[19] *Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

[20] C. H. Scholer, *Examination and Study of Certain Structures in the Pacific Ocean Area*, Progress Report, USNCEL Contract NBy-3171 (USN CEL, June 1959).

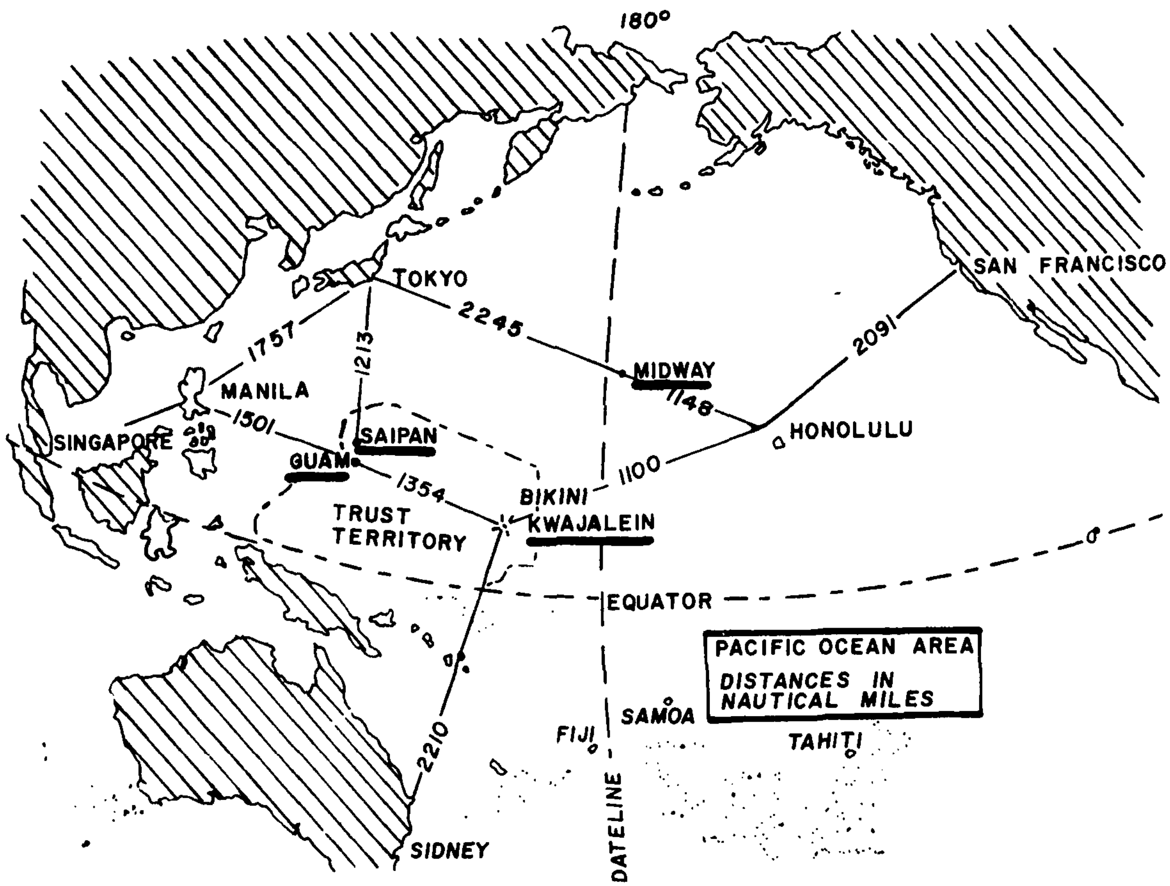

Figure 1. Pacific Ocean area.

Table 1

Description of Guam, Saipan, Kwajalein, Midway

	Guam	Saipan	Kwajalein	Midway
Location & Extent	Latitude: 13°28' N Longitude: 144°45' E Largest and southernmost of the Mariana Islands. It is about 30 mi long and between 4 and 11 mi wide. Land area exclusive of reefs is 212 sq mi.	Latitude: 15°13' N Longitude: 145°44' E Second largest among the Mariana Islands. It is about 13 mi long and 4 mi wide. Land area exclusive of reefs is about 48 sq mi. It is located about 140 mi northeast of Guam.	Latitude: 8°45' N Longitude: 167°43' E Kwajalein Atoll is located in the "Ralik" chain of the Marshall Islands. The atoll is in the shape of a crescent loop inclosing a lagoon. The atoll consists of approximately 100 small islands with a total land area of 5.6 sq mi. Kwajalein is the largest with an area of 1.2 sq mi and is located in the extreme southeastern corner.	Latitude: 28°12'35" N Longitude: 177°22'47" W Midway Island is a part of the Leward Islands of the Hawaiian Archipelago. The atoll consists of only two islands, Sand and Eastern. Sand Island, the largest, is approximately 13,000 ft long by 6000 ft wide and consists of 1.88 sq mi.
Physiography	It is composed of volcanic flows and tuffs partly covered by coralline limestones.	It is similar to Guam, volcanic in origin and is composed of volcanic flows and tuffs partly covered by coralline limestones.	The atoll is a coral reef formation. Such coral atolls are believed to be seamounts which have been capped by calcareous marine growth. Presumably the lower parts are composed of nonlimey rocks, usually of volcanic origin.	The atoll is a coral reef formation geographically similar to but much smaller than the Kwajalein atoll.
CLIMATE Temperature	Annual mean temperature is 80.9°F. Annual mean temperature variation is 3.3°F. Daily temperature range is 10 to 12°F.	Annual mean temperature is 78°F. Annual mean temperature variation and daily temperature range data is not available but is assumed relatively uniform.	Annual mean temperature is 84°F. Annual mean temperature variation is 2°F. Daily temperature range is 10 to 12°F.	Annual mean temperature is 72°F. Annual mean temperature variation is 13°F. Daily temperature range is 10°F.
Humidity	Range - Day: 65 to 80% Range - Night. 85 to 100%	Monthly average is 79 to 86%.	Range - Day: 76% Range - Night: 83%	Range - Day: 71% Range - Night: 82%
Rainfall	Annual mean rainfall is 70 in. Seasons: Dry seasons are January through May. Wet seasons are July through November.	Annual mean rainfall is 90.7 in. Seasons: Dry seasons are November through June. Wet seasons are July through October.	Annual mean rainfall is 102 in. Seasons: Dry seasons are January through April. Wet seasons are June through November.	Annual mean rainfall is 40.26 in. Seasons: due to the latitude there is winter-summer season with winter being December through March.

Table I (cont'd.)

	Guam	Saipan	Kwajalein	Midway
Wind	Velocity and Direction: Dry season: easterly, + 15 mi per hr. Wet season: no prevailing direction, speed less than 15 mi per hr, calms are frequent.	Direction: Dry season, northeast continual trade winds. Wet season: shifting wind direction and velocity.	Velocity and Direction: east northeast trade winds December through June (Average velocity of 16 mi per hr). Weaker and more easterly winds occur during the other months.	Velocity and Direction: prevailing wind east northeast, average velocity of 10.2 mi per hr.
Oceanography and Reefs	Approximate ocean temperature is 81 F. Reef formation: Guam is completely encircled by fringing reefs except along parts of the limestone cliffs. In two places, Apra Harbor and Cocos Island, barrier reefs inclose or partly inclose small lagoons.	A coral-algal barrier reef and narrow lagoon borders Saipan on the west, and a narrow ringing reef occurs discontinuously around much of the rest of the island.	The atoll reefs lie at a inter-tidal level, mostly exposed at low tide and submerged at high tide.	The atoll reef is small, about 4 mi in diameter, and is open on the western side.

on occasion coral rubble. Conventional quarrying techniques, blasting, hauling, crushing and screening, were used. Both quarries produced coarse and fine aggregate. The screening operation of each facility was wet, using fresh water, though one quarry did continually recycle its water (Figures 3 and 4).

Three concrete batch plants were visited at Guam (Figure 4). The three batch plants were set up for transit mixer operations, though one batch plant also mixed the concrete. All plants batched by weight proportioning. The batch-mixer plant was a modern computer-operated facility that automatically adjusted the mix water quantity for aggregate moisture content. The other batch plants were not set up to either monitor or automatically adjust for aggregate moisture content.

Saipan. Saipan, like Guam, had an abundance of suitable rock material for aggregate production. Hard coralline limestone was available and easily accessible. Volcanic rock, suitable for aggregate production, occurred sporadically but was rather inaccessible. Natural gravel existed only in very limited quantities and sand was limited to beach areas along the west coast.

Two active quarry operations were visited during the field evaluation. One was commercial; the other was non-commercial and directly supported a construction contract. The quarry supporting the construction effort was a small quarry, crusher, and batch plant operation (Figures 5 and 6). The commercial quarry was larger, but small by United States standards, even though it was the only commercial aggregate source on the island (Figures 7 and 8). Both quarries produced coarse and fine aggregate from coralline limestone formations on the west side of the island. The commercial quarry used a wet screen operation to separate coarse and fine aggregate. The non-commercial quarry separated by dry screening since water was not readily accessible at the quarry site.

Concrete batching facilities at Saipan consisted of two plants each supporting one of the above quarries. Both plants batched by weight proportioning. Neither was equipped to monitor or automatically adjust for aggregate moisture content. The batch plant used by the construction company, consisting of a single scale and conveyor (Figure 6), was an example of the simplicity of some of the equipment used.

a. Hawaiian rock quarry, Guam.

b. Hyundai Quarry, Guam.

Figure 2. Commercial quarries operated on Guam.

Figure 3. Recycling water for wash screens, Hyundai Quarry, Guam.

Figure 4. Concrete batch plant and transit mixer, Hyundai Quarry, Guam.

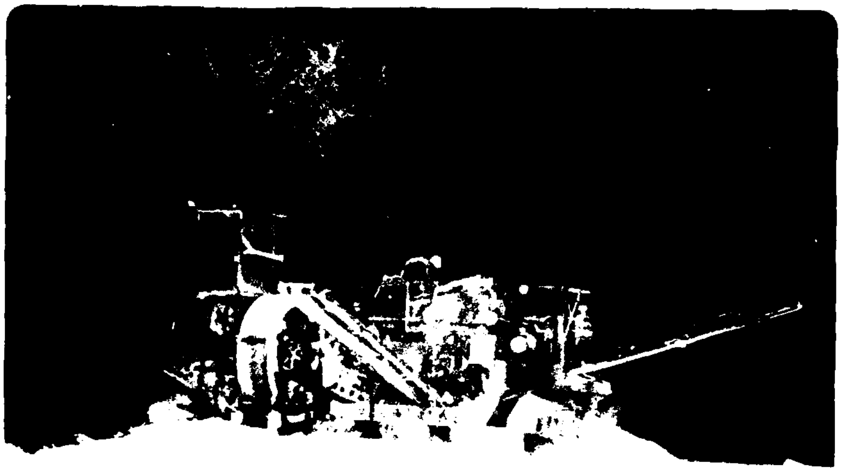

Figure 5. Crusher and screens, Black Quarry, Saipan.

Figure 6. Batch plant, Black Quarry, Saipan.

Figure 7. Dillingham Quarry, Saipan.

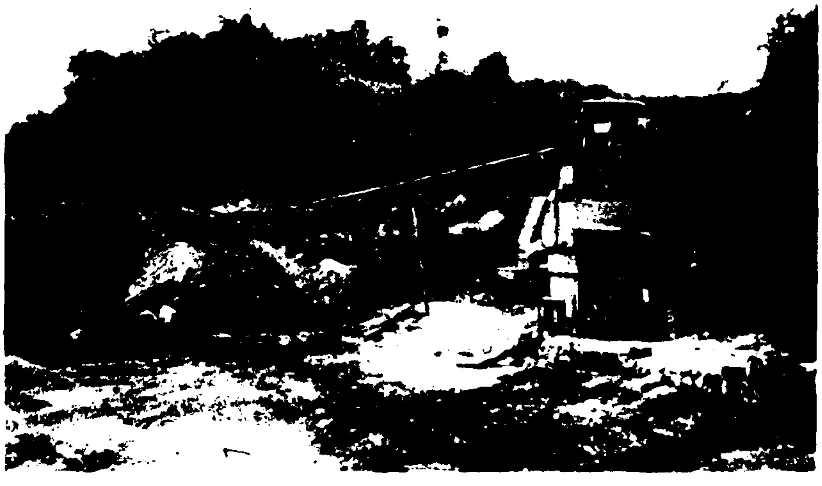

Figure 8. Crusher and screens, Dillingham Quarry, Saipan.

Kwajalein. Kwajalein Island is part of a coral atoll. Coral atolls by their nature do not offer any non-coralline derived material suitable for aggregate production. The island is composed of loose, poorly-consolidated, calcareous material derived from foraminifera, coral shells, and marine algae or their debris, a result of the destructive action of the elements. The island is flat with an average elevation of 5.9 ft and few natural points exceeding 15 ft above mean sea level.

No active quarrying or aggregate processing was observed during the field evaluation. One recently active quarry site was visited. The site, a fringing reef, was located on the south side of Kwajalein. Coral was quarried only from the middle of the reef leaving undisturbed approximately 100 ft of reef on both the ocean and land side (Figure 9). The depth of the quarry appeared to be about 10 ft.

The aggregate crusher was being dismantled for storage during the field evaluation. The crusher consisted of a primary 30-inch maximum size jaw crusher and triple deck shaker screens. Oversize material rejected by the shaker screen was fed to a separate roller-crusher and returned to the screens (Figure 10). Seawater was used to wash the aggregate on the screens.

No concrete was being batched during the field evaluation but a 6 cu yd portable plant with a three compartment aggregate bin was on-site. The plant was set up to load transit mixers. Batching was by weight proportioning though equipment to monitor or automatically adjust for varying aggregate moisture contents was lacking.

Midway. Midway is a small coral atoll consisting of two islets, Sand and Eastern. Like Kwajalein, Midway does not offer any non-calcareous material suitable for aggregate production. During the field evaluation, no quarrying, aggregate processing, or concrete batching was observed. Also there was no aggregate processing or concrete batching equipment on the island other than small mixers used by the maintenance and repair personnel. Discussions with personnel on the staff of the Navy Officer In Charge of Construction (OICC), Mid-Pacific, indicated that coral was not being used as an aggregate for any concrete placed above grade at Midway. Concrete aggregate for Midway was crushed igneous rock barged from Honolulu.

Coral Concrete Structures. The condition and integrity of the structures built with coral concrete varied drastically. The only noted deterioration was the cracking and spalling of concrete that covered corroding reinforcing steel. The corrosion and spalling problem was observed on all the islands though the intensity of the problem varied. Table 2 contains a per structure analysis of all major structures included in the field evaluation. The table contains structure location, age, condition and aggregate source. The following is a per island summary of structure condition and probable cause of deterioration.

Guam. Numerous reinforced concrete structures have been built on Guam. Of the total only a few showed signs of significant or unusual deterioration. The structures in the poorest condition were Piti Power Plant No. 1, BOQ Buildings 27000 and 27001 at Anderson AFB, and the covered walkway at the Naval Station. The deterioration of the walkway and Buildings 27000 and 27001 consisted of cracked and spalled concrete cover over corroding reinforcing steel. In both cases the poorest deterioration was limited to exterior columns (Figures 11 and 12). At the BOQ complex, it was observed that the concrete cover over the corroding reinforcing steel had been less than 1 inch thick (Figure 13). Core samples taken from the walkway columns indicated that the reinforcing steel was not always centered inside the columns. Cover on one side was often less than half an inch, while cover on the opposite was more than 3 inches. The evaluation of the Piti Power Plant indicated that considerable deterioration had occurred primarily at the basement level of the older plant (No. 1). The deterioration consisted of massive cracking and spalling concrete and corroding reinforcing steel. In some isolated instances deterioration was sufficient to impair the integrity of the structure. One possible cause for the deterioration is that brackish water often seeps into the lower level of the structure. One local source indicated that the concrete mix water was brackish (records were not available to substantiate this).

Saipan. The number of concrete structures available for evaluation at Saipan was limited. The following were the basis for the field evaluation: the

Figure 9. Quarry site, Kwajalein (inactive).

Figure 10. Crusher and screen, Kwajalein.

Table 2

Structure Evaluation

Structure Location	Structure Frame	Type Walls	Date Built	Current Use	Aggregate Type & Source	Current Condition of Structure
Guam						
Anderson AFB						
Bldg. 27000 & 27001	R/C	Concrete & Block	early 1950's	BOQ	Guam	Concrete surfaces of exposed columns and floor beams were cracked and spalled. The spalled surfaces exposed reinforcing bars which were badly corroded.
Bldg. 21000	R/C	Concrete & Block	1952	Service Complex	Coralline Limestone, Guam	Concrete surface on underside of exterior cantilever walkway cracked and spalled along outer edge. Spalled concrete exposed base plate of steel railing.
Piti Power Plant						
Bldg. 1	R/C	R/C	1951	Power Generation	Coralline Limestone, Guam	Concrete surfaces, primarily in the basement, have cracked and spalled revealing deeply corroded resteel.
Bldg. 2	R/C	R/C	mid 1960's	Power Generation	Coralline Limestone, Guam	No significant deterioration was observed.
NAVMAG						
Magazines	R/C	R/C	early 1950's to late 1960's	Ammo Storage	Coralline Limestone, Guam	Numerous magazines had small hairline cracks that allowed for rapid moisture migration through the concrete, though major concrete spallation and or rebar corrosion was not observed.
NAVSTA						
Covered Walkway	R/C		early 1950's	walkway	Coralline Limestone, Guam	At numerous locations concrete surfaces of the columns were spalled revealing corroded tie bar resteel.
Saipan						
High Comm. House		R/C	1955	Abandoned	Coralline Limestone, Guam	No significant deterioration was observed.
T.T. P.W. Test Lab	(floor)	Concrete	1968	Test lab	Coralline Limestone, Saipan	No significant deterioration was observed.
Japanese Hospital	R/C	R/C	1930's	Abandoned	Limestone	Concrete surfaces throughout the building were cracked and spalling revealing corroded resteel.
Isley Shelter #2	R/C	R/C	Pre WWII	Abandoned	Igneous Rock	No significant deterioration except WW II shell damage had occurred and not been repaired.
Kwajalein						
DCCB Bldg. 1800	R/C	R/C	1971	Storage	Reef Coral South Loi	No significant deterioration was observed.
Cold Storage Bldg 610	R/C	R/C	1953&68	Cold Storage	Reef Coral South Loi	No significant deterioration was observed.
Pacific BQ Bldg 704	R/C	R/C	1952	Housing & Retail Store	Reef Coral South Loi	Slight cracking of concrete surfaces covering resteel was noted.
Transient Hotel Bldg 908	R/C	R/C	1957	Housing	Reef Coral South Loi	Building was under repair during field evaluation. The repair consisted of replacing spalled concrete and the exposed resteel that was badly corroded.
KMR HQ Bldg 901	R/C	R/C	1954	Headquarters & Air Terminal	Reef Coral South Loi	A small amount of local concrete cracking and spallation was observed.

Table 2 (cont'd.)

Structure Location	Structure Frame	Type Walls	Date Built	Current Use	Aggregate Type & Source	Current Condition of Structure
Midway						
Pacific Cable Sta. 649, 633, 643, 628	R C steel	R C	1906	Housing	Unknown	No significant deterioration was observed.
Communication Bldg 521	R C	R C	1942	Communications	Unknown	Major concrete spallation was observed. One entire wall was spalled revealing mesh reinforcement.
Barracks Bldg 3504-05	R C	R C & Block	1957	Housing-Bachelor	Channel-Dredged Coral Midway	Several R C beams and columns were severely cracked.
Mess Hall Bldg 3502	R C	R C & Block	1957	Food Preparation & Service	Channel-Dredged Coral-Midway	Nearly all R C columns were severely cracked.
Hanger Bldg 3506	Steel	R C & Block	1958	Hanger & Maintenance Facilities	Channel-Dredged Coral-Midway	Slight and local cracking of some R C walls and beams.
School Bldg 6346	R C	R C & Block	1958	School	Channel-Dredged Coral-Midway	No significant deterioration was observed.
Control Tower Bldg 5307	R C	R C	1957	Control Tower	Channel-Dredged Coral-Midway	Concrete covering resteel in several locations was spalled revealing badly corroded resteel.

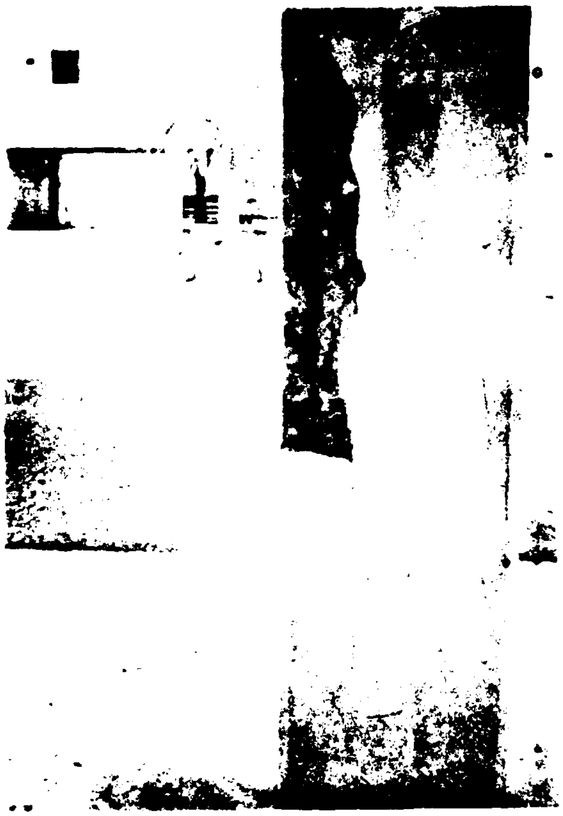

Figure 11. Exterior column, **BOQ building 27000 and 27001, Anderson AFB, Guam.**

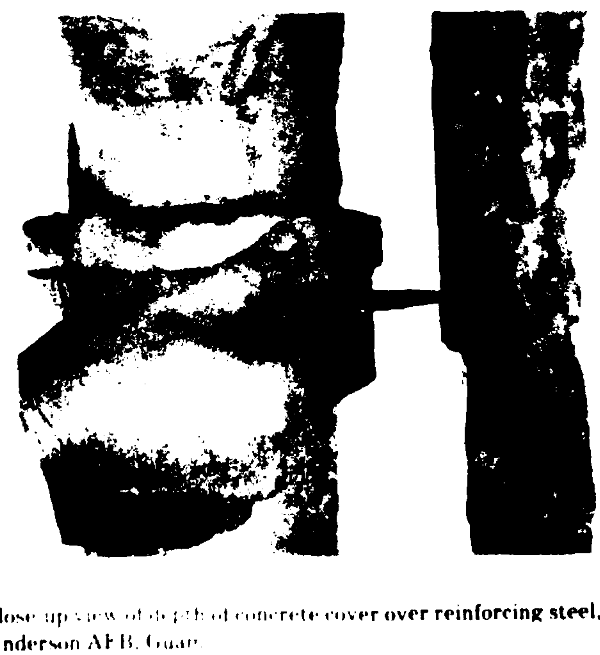

Figure 12. Close up view of depth of concrete cover over reinforcing steel, exterior column BOQ building 27000. Anderson AFB, Guam.

Figure 13. Column, Naval station walkway, Guam.

Figure 14. Abandoned Japanese hospital, Saipan.

High Commissioner's residence, the Trust Territory Public Works Test Lab, and two abandoned Japanese facilities (a hospital and a munitions shelter). The hospital showed signs of significant deterioration (Figure 14). Since the structure had been abandoned during World War II its significance was questionable. No significant deterioration was noted at the other structures except for some unrepaired shell damage at the munitions shelter.

Kwajalein. The Kwajalein missile complex contains a multitude of reinforced concrete structures. Only a few representative structures were selected for field evaluation. In general the field evaluation indicated that cracking and spalling concrete and corrosion of reinforcing steel has been a significant problem, but due to a well staffed maintenance and repair operation most of the structures did not show signs of distress. Maintenance personnel indicated that the windward side of all structures, and especially those structures on the windward side of the island, required more maintenance than similar structures on the leeward side. A review of maintenance records for the period 1965 to 1972 showed that all structures in the field evaluation, excluding the new Defense Center Control Building (DCCB), had received some maintenance to repair cracked and spalled concrete.

Midway. Conditions at Midway were considerably different from those at the other islands. Many reinforced concrete structures had deteriorated sufficiently to impair their integrity. As with the other islands, the major source of distress was spalling concrete and corroding reinforcing steel. Figures 15 - 20 are indicative of the corrosion and spalling problem at Midway. The poorest conditions were observed at Communications Building 521

Figure 15. Shear wall Communications Building 521, Midway.

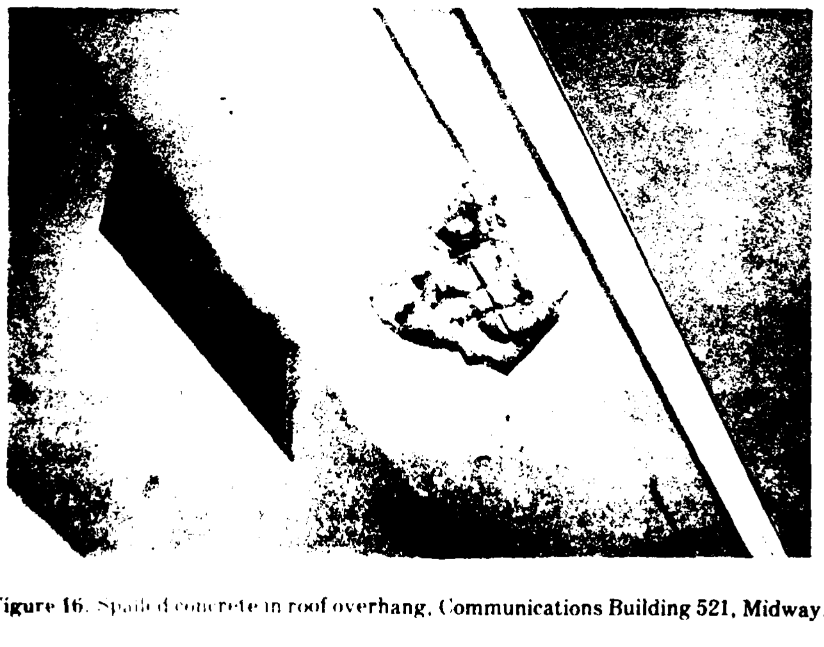

Figure 16. Spalled concrete in roof overhang, Communications Building 521, Midway.

Figure 17. Reinforced concrete beam, barracks building 3504, Midway.

Figure 18. Reinforced concrete column, mess hall building 3502, Midway.

Figure 19. Second deck walkway, cable building, Midway.

Figure 20. Vertical concrete wall above doorway, hangar, Midway.

where the concrete face of a shear wall had spalled back to the first layer of reinforcement (Figure 15), and at Control Tower Building 5307 where large areas of concrete had been spalled revealing very corroded reinforcing steel. The deterioration at the mess hall and barracks complex was less extensive but equally severe.

3 ANALYSIS OF DOCUMENTED INFORMATION

Construction Specifications. In general, specifications controlling production of coral aggregate and coral concrete were similar to specifications for conventional aggregate and concrete. Supplementary notes to the Navy's standard concrete specification[21] indicate that hard reef coral or finger coral may be used as an aggregate for concrete in the Pacific islands. According to the notes, grading, methods of sampling and testing, and permissible amounts of deleterious substances for coral shall comply with American Society of Testing and Materials (ASTM) Standard Specification C33 except for grading limits on fine aggregate. The use of finger coral shall be limited to concrete with 28-day compressive strengths not more than 2000 psi. It was also recommended that reef coral rock should have a specific gravity of not less than 2.40. Because of the high rate of absorption of coral, it is recommended that volumetric proportioning of coral concrete be used in locales where humidity is high and where sudden, violent rainfall occurs. The water/cement ratio should be controlled by slumps established under controlled conditions.[22]

In most cases, concrete specifications developed by the Corps of Engineers for use at Kwajalein were similar to the above NAVFAC Specification 13Yh. The major differences were that the Corps specifications did not list any specific gravity limits for coral aggregate nor was there a requirement for weight proportioning of coral concrete.

The concrete specifications used by the Navy OICC Marianas at Guam and Saipan were also slightly different from the 13Yh specification. OICC Marianas requires that coralline limestone used to produce concrete aggregate have a specific gravity not less than 2.50. Volumetric batching was not permissible.[23]

Table 3 lists the gradation requirements for fine aggregate used by the Corps of Engineers at Kwajalein and the Navy OICC Marianas at Guam and Saipan. Comparison of these gradation requirements with ASTM Standard Specification C33 or Federal Specification SS-A-281 indicates only a slight difference.

Table 3

Fine Aggregate Gradation Requirements

Sieve Size	Percentage by Weight Passing: Corps of Eng. Spec. for Kwajalein	OICC Marianas Spec. for Guam & Saipan	Fed. Spec. SS-A-281
3/8 in.		100	100
4#	95-100	95-100	95-100
8#	75-95	70-90	80-100
16#	55-85	45-75	50-85
30#	30-60	25-55	25-60
50#	12-30	10-30	10-30
100#	5-10	2-10	2-10

Construction Techniques. The techniques used in producing coral aggregate and coral concrete are similar to those for conventional aggregate and concrete.

The construction of the AEW facilities at Midway was documented in the Indenco Engineers report.[24] It indicated that all concrete was made from coral aggregate and brackish water. The aggregate was obtained by channel dredging augmented by blasting. After dredging all aggregate was screened and the fines stockpiled separately. All coarse material was dried in a rotary kiln, crushed, graded, and stockpiled. The aggregate was not washed and no attempt was made to leach any of the salt. The salinity of the mix water varied from 1800 to 3000 ppm with a weighted average of about 2600 ppm.

[21] *Concrete Construction*, NAVFAC Specification 13Yh (1967).
[22] *Concrete Construction*.

[23] Bolys Ciurlionis, *Coral Aggregate in A C Pavement and Concrete Construction*, Technical Note SSFO 70-1 (Seabee System Engineering Office, 1970).
[24] *Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

Table 4 lists average specific gravity, absorption, and gradation for the coral aggregate. Table 5 shows the concrete mix proportions. The average compressive strength for the 2500 psi mix was 3894 psi in 28 days, and for the 3000 psi mix, 4701 psi in 28 days. The range of 28-day strengths for the 2500 psi mix was 3300 to 4400 psi, and for the 3000 psi mix 3600 to 5000 psi.[25]

Table 4

Average Aggregate Gradation, Specific Gravity, and Absorption for AEW Construction

Midway*

(Percent Passing)

Sieve Size	Fines 3/8 in. - 0	Coarse 3/4 - 3/8 in.	1 1 - 3/4 in.
1	—	—	100
3/4 in.	—	100	59
1/2 in.	—	48	4
3/8 in.	100	14	3
#4	87	2	2
#8	67	2	2
#16	50	1	2
#30	35	1	1
#50	21	1	1
#100	9	1	1
Specific Gravity	2.48	2.34	2.33
Absorption	5.6	6.7	6.6

**Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

Table 5

Coral Concrete Mix Designs
Navy OICC Marianas
Mix Design (1 in. max Agg)

Design Strength	Cement bag/Cy yd	Water gal/bag cement	Fine Agg. % of Total Agg.
2000	4.2	8.25	46
2500	4.8	7.25	45
3000	5.3	6.25	44
4000	6.6	5.0	42
Corps of Engineers Mix Design Kwajalein* (3/4 in. max Agg)			
2000	4.5	7.7	43
2500	5.0	7.1	43
3000	5.6	6.58	45
4000	6.0	5.85	43
AEW Facilities Midway Mix Design* (1 in. max Agg)			
2500	5.75	6.56 Avg (range 6-7)	49-51
3000	6.60	5.77 Avg (range 5-6)	49 - 51
Kwajalein Mix Design Oct. 1953 (3/4 in. max Agg)			
3000	6.5	6.25	47
Guam Mix Design 1953-54 (Fadian point Agg)			
2000	5.0	8.0	49
3000	6.0	6.43	49
4000	7.0	5.41	49
1953-54 (Pati Point Agg)			
3000	5.7	6.77	50

*Air content 6%.

Information on construction at Kwajalein was more sketchy because the island has been under both Navy (1945-1964) and Army (1964-present) control, and construction has been performed by several civilian contractors (Mid-Pac, Burns, Fisher, and Pacific-Martin-Zachry) and Navy Seabees. Records indicate that all concrete at Kwajalein was made with coral aggregate.

Originally, coral aggregate was obtained by dredging channels and harbors. The quality of the concrete produced from the dredged aggregate was poor because of the sharp pieces, softness, friability, and lack of uniformity in the coral sediments. In 1954 removal of reef coral was initiated by the Navy at Kwajalein in an effort to find a more uniform and durable aggregate source. Because of the limited volume of rock available at the original Kwajalein quarry, in 1955 the Navy opened a quarry on the ocean reef east of South Loi Island. The South Loi quarry was used by the Navy and later by the Army until 1969. More than 150,000 cu yds of coral aggregate and revetment armor stone were excavated from the quarry at South Loi. The quarrying procedure was to drill and load with explosives at low tide while the reef was exposed. Blasting was done after the reef was covered by incoming high tides. Loading and hauling from the quarry to the crusher was also

[25]*Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

accomplished at low tide. Figure 21 contains gradation curves for typical aggregate produced at South Loi.

Mix water for concrete at Kwajalein was originally brackish water pumped from wells, but after 1953 when catchment areas on the airfield were developed, there was sufficient fresh water to allow for fresh water mixing of concrete.

Concrete proportioning at Kwajalein during the early Navy control (at least through 1953) was conducted on a volume basis. Concrete proportioning during the more recent Army construction required weight proportioning. Table 5 contains mix designs used during both the early Navy control and the later Army control period.

Data on concrete construction at Guam indicates that as late as 1947 a great deal of the concrete fabricated at Guam incorporated cascajo coral aggregate. Cascajo was unsatisfactory as an aggregate due to its low durability. The cascajo was comprised of large amounts of soft particles and therefore had no appreciable strength or abrasion resistance. Prior to 1952 the principal difficulties encountered in coral concrete fabrication at Guam were use of low quality coral, haphazard grading, poor uniformity of concrete as it was discharged from the mixer, and inferior placing and curing of concrete. Table 5 contains mix designs that were used in the early 1950's and the late 1960's and early 1970's.

Very little data was found regarding construction at Saipan.

Structural Deterioration. Records of four previous field evaluations were found. The earliest evaluation recorded in a memorandum by Glenn V. Joines contained no pertinent information on the conditions of the reinforced concrete structures on the island.[26] Joines did indicate that the on-going construction was poorly executed.

Two later studies were conducted in 1959. One study by C. H. Scholer involved evaluating reinforced concrete structures on the islands of Midway, Kwajalein, and Guam.[27] The other report by Indenco Engineers, Inc., contained an evaluation of reinforced concrete structures at Midway.[28]

Field evaluations (reported herein) of structures at Kwajalein, Midway, and Guam were also included in the Scholer and Indenco reports. Major changes were observed when the findings of the earlier studies were compared with the findings of this study. The earlier studies of the Navy AEW facilities at Midway attributed the majority of the spalled and cracked concrete to the corrosion of embedded conduit. The present evaluation indicated that corrosion of reinforcing steel was the major factor affecting structure deterioration. Due to the efficient maintenance and repair operation at Kwajalein, direct comparison of the earlier and present field evaluations was difficult. The Scholer study pointed out that the Pacific BOQ (Building No. 704) showed signs of seriously corroding reinforcing steel in the beams on the second deck. Information obtained for the present study indicated that in 1968 the building underwent major rehabilitation including significant structural repairs.

Scholer reported the Piti Power Plant as the only structure on Guam that showed signs of serious deterioration. He indicated that the most extensive deterioration had occurred in the basement along load bearing walls of the power plant. He also noted that several places on the first floor showed severe corrosion of reinforcing steel and spalling of concrete. The present study found that conditions at the power plant had not changed significantly since Scholer's study; however, other deterioration problems were discovered on Guam (Anderson AFB Buildings 27000 and 27001 and the Naval station walkway).

The most recent field evaluation was conducted by the Engineering Department, Public Works Center, U.S. Naval Station—Guam, on BOQ Buildings 27000 and 27001, Anderson AFB.[29] The evaluation was conducted during February 1972. Results

[26]Glenn V. Joines, *Inspection Trip to Kwajalein from 17 October to 27 October 1953* (November 1953).

[27]C. H. Scholer, *Examination and Study of C...ain Structures in the Pacific Ocean Area*, Progress Report, USNCEL Contract NBy-3171 (USN CEL, June 1959).

[28]*Engineering Study, Recommendations and Estimates for Repair to AEW Facilities at U.S. Naval Station Midway Islands* (Indenco Engineers, Inc., March 1960).

[29]*Engineering Report on Cracking of Reinforced Concrete Columns of BOQ Building Numbers 27000 and 27001, Anderson Air Force Base, Guam* (U.S. Navy, 1972).

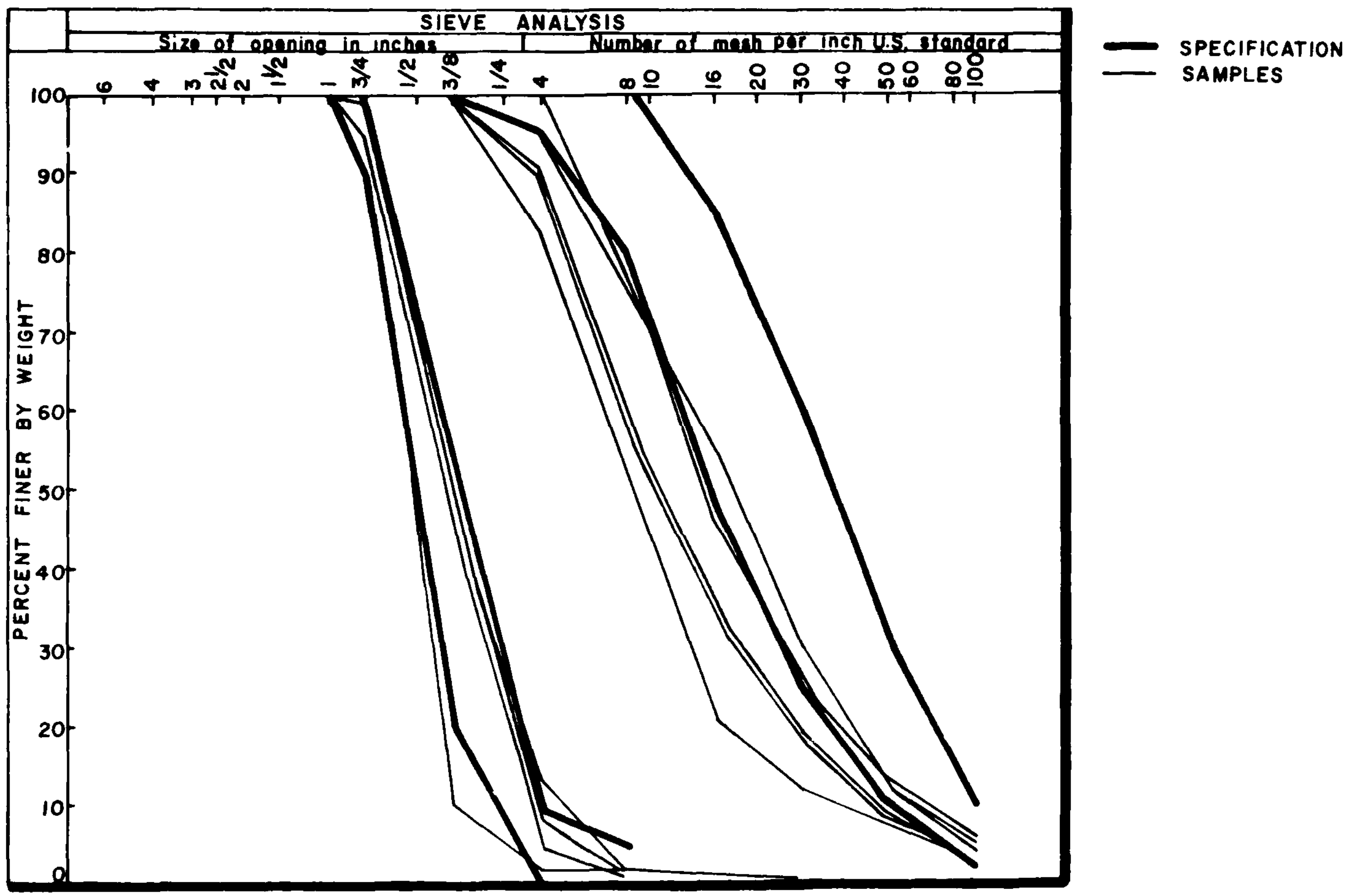

Figure 21. Gradation curves for typical aggregate produced at South Loi.

were very similar to the results contained in this report.

Inspection Records. Inspection records were available only for recent construction at Kwajalein. These records covered the results of control tests on concrete for the DCCB, Altair, Muk Island Control Building (MICB), and various other small building projects. Incomplete records often made analysis of data difficult. Water-cement ratios were ambiguous (numerical values were not specified volumetrically or gravimetrically) and data sheets showed that many of the control cylinders for the MICB facility were taken above their design strength, but never loaded to ultimate capacity. Table 6 contains, on a per mix design basis, mean and coefficient of variation values for slump, air content, density, and compressive strength. Coefficients of variation obtained from the compressive tests, when compared with ACI recommended standards,[30] indicate that quality control for most mixes varied from good to fair with a few mixes having poor control.

Quality control charts were also used to evaluate trends and the influence of seasonal changes on the compressive strength of concrete. For 28-day specimens Figure 23 depicts per day averages for all 3000 psi design mixes used on the DCCB facility. Figure 22 is a moving average plot of the same data. Each point of the moving average is the average of the previous 5-day averages. Figure 23 denotes the large amount of scatter in the test data from day to day. This was also noted by the size of the coefficients of variation in Table 6. The moving average plot, Figure 22, indicates that trends did occur, but attempts to relate the trends to precipitation conditions were fruitless.

4 LABORATORY TEST RESULTS

During the field evaluation, aggregate and concrete samples were collected for laboratory analysis. Aggregate samples were obtained from each active quarry visited. Concrete samples were normally 6 or 8-inch diameter cores obtained from selected structures on each of the islands visited except Midway. On three occasions chunks of spalled concrete were collected for analysis. Table 7 lists the structures from which concrete samples were collected. Laboratory tests determined the absorption capacity and specific gravity of the aggregate samples and the chloride ion content of both the aggregate and concrete samples.

Table 8 shows the results of the specific gravity, absorption, and chloride ion tests on the aggregate samples. With the exception of the Midway dredged material (which was not used as a concrete aggregate), the specific gravity (SSD) of the coral varied from 2.34 to 2.53 and the absorption capacities from 2.5 to 5.9 percent. Specific gravity values were lower and absorption values were higher than normal values obtained for concrete aggregate. However, neither the specific gravity nor the absorption capacities were sufficiently beyond the normal range to directly affect the quality of concrete produced. High absorption capacities do influence variability in the quality of concrete if the moisture condition of the aggregate is unknown. If the aggregate is proportioned as saturated surface dry when it is really air dry, the resulting mix is harsher and stronger than expected. Conversely, if the aggregate is proportioned as air dry when it is saturated, the resulting mix will be less harsh and of a lesser strength than expected.

A titration-electrode technique was used to determine total chloride content of the aggregate and concrete samples.[31] Results of the chloride test on the aggregate samples indicated that the salt content of all aggregate samples was near zero (Table 8). This was even true for the reef coral material from Kwajalein. However, the aggregate samples were only collected from the periphery of the stockpiles where the leaching of the salt by rain water was most intense. Thus it cannot be assumed that chloride content of the entire stockpiles was as low.

The procedure for analyzing the chloride content of concrete was to recore the 6 and 8-inch diameter samples down to 4 inches, using a dry coring procedure; and then, using a dry saw, slicing the 4-inch diameter samples into 2-inch slices. The dry coring

[30] "Recommended Practices for Evaluation of Compression Test Results of Field Concrete (ACI 214-65)," *ACI Manual of Concrete Practice, Part I* (1968).

[31] H. A. Berman, "Determination of Chloride in Hardened Portland Cement Parts, Mortars and Concrete," *ASTM Journal of Materials*, Vol 7, No. 3 (September 1972), pp 330-335.

Table 6

Concrete Cylinder Test Results—Kwajalein

Building	No. of Observations	Cyl Age (days)	Cement (bags/yd^3)	W/C	Mean Slump (in.)	Slump C.V. (%)	Mean Air Entrainment	Air C.V. (%)	Mean Density (lbs/ft^3)	Density C.V. (%)	Mean Cyl. Str. (psi)	Cyl. Str. C.V. (%)	Design Strength (psi)	No. of Obs. Below Design Str. (%)
DCCB	81	7	5.6	?	3.49	15.9	5.62	8.4	137.8	.90	2928	19.5	3000	55.6
DCCB	56	7	5.6	.53	3.23	17.9	5.55	6.4	137.4	.76	2963	13.8	3000	50.0
DCCB	35	7	5.6	.58	2.45	27.7	5.78	12.7	137.0	1.64	2282	30.5	2500	71.5
DCCB	20	7	5.6	.59	2.47	34.0	5.22	10.0	138.0	1.00	2041	22.8	2500	90.0
DCCB	35	7	6.0	.49	2.53	26.2	5.00	12.4	142.6	1.35	3378	12.3	3000	11.4
DCCB	22	7	6.0	.52	2.34	26.6	5.32	11.7	141.2	1.57	3234	11.9	3000	31.8
DCCB	243	7	6.0	.53	2.80	22.2	5.68	14.5	139.9	1.44	3274	19.0	3000	30.9
DCCB	8	7	6.0	.59	2.56	24.3	5.10	4.2	139.0	.67	3113	10.7	3000	37.5
DCCB	110	28	5.6	.53	3.23	17.9	5.56	6.2	137.4	.76	4021	12.0	3000	0.91
DCCB	156	28	5.6	?	3.51	15.9	5.61	8.4	137.8	.91	3913	13.9	3000	1.28
DCCB	47	28	5.6	.58	2.46	25.5	5.72	12.2	136.9	1.56	3430	22.1	2500	10.6
DCCB	33	28	5.6	.59	2.39	32.0	5.21	36.1	138.0	.85	3307	15.9	2500	0.00
DCCB	54	28	6.0	.49	2.47	26.9	4.99	12.8	142.7	1.45	4159	11.8	3000	1.85
DCCB	37	28	6.0	.52	2.39	26.6	5.29	12.0	141.3	1.58	4194	14.7	3000	2.70
DCCB	271	28	6.0	.53	2.85	22.4	5.65	14.3	139.7	1.70	4170	15.3	3000	1.84
DCCB	15	28	6.0	.59	2.60	23.2	5.09	4.2	139.1	.64	4466	8.1	3000	0.00
Altair	64	7	6.0	?	2.80	26.1	5.78	7.94	?	?	2780	20.7	3000	63.5
Altair	91	28	6.0	?	2.81	27.7	5.75	7.22	?	?	3396	20.7	3000	19.8
MICB	231	7	6.0	?	2.61	18.7	5.21	10.5	133.4	2.35	3554	16.5	3000	18.6
MICB	54	7	6.0	.53	2.69	11.5	6.03	14.7	?	?	3404	24.7	3000	24.1
MICB	458	28	6.0	?	2.61	18.6	5.20	10.6	133.4	2.35	4076	7.2	3000	.88
MICB	140	28	6.0	.53	2.65	11.1	6.24	16.1	?	?	3889	21.1	3000	15.0

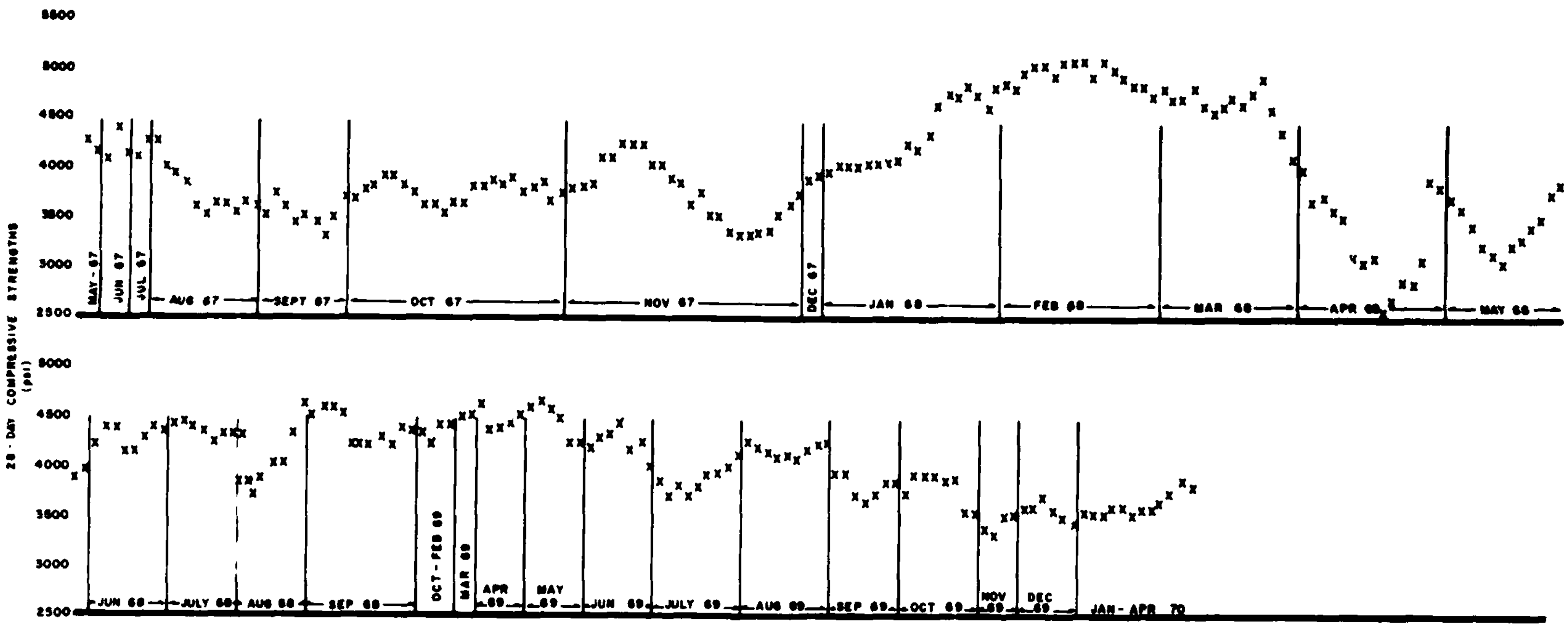

Figure 22. Graph of 5 day average values, WCCB building.

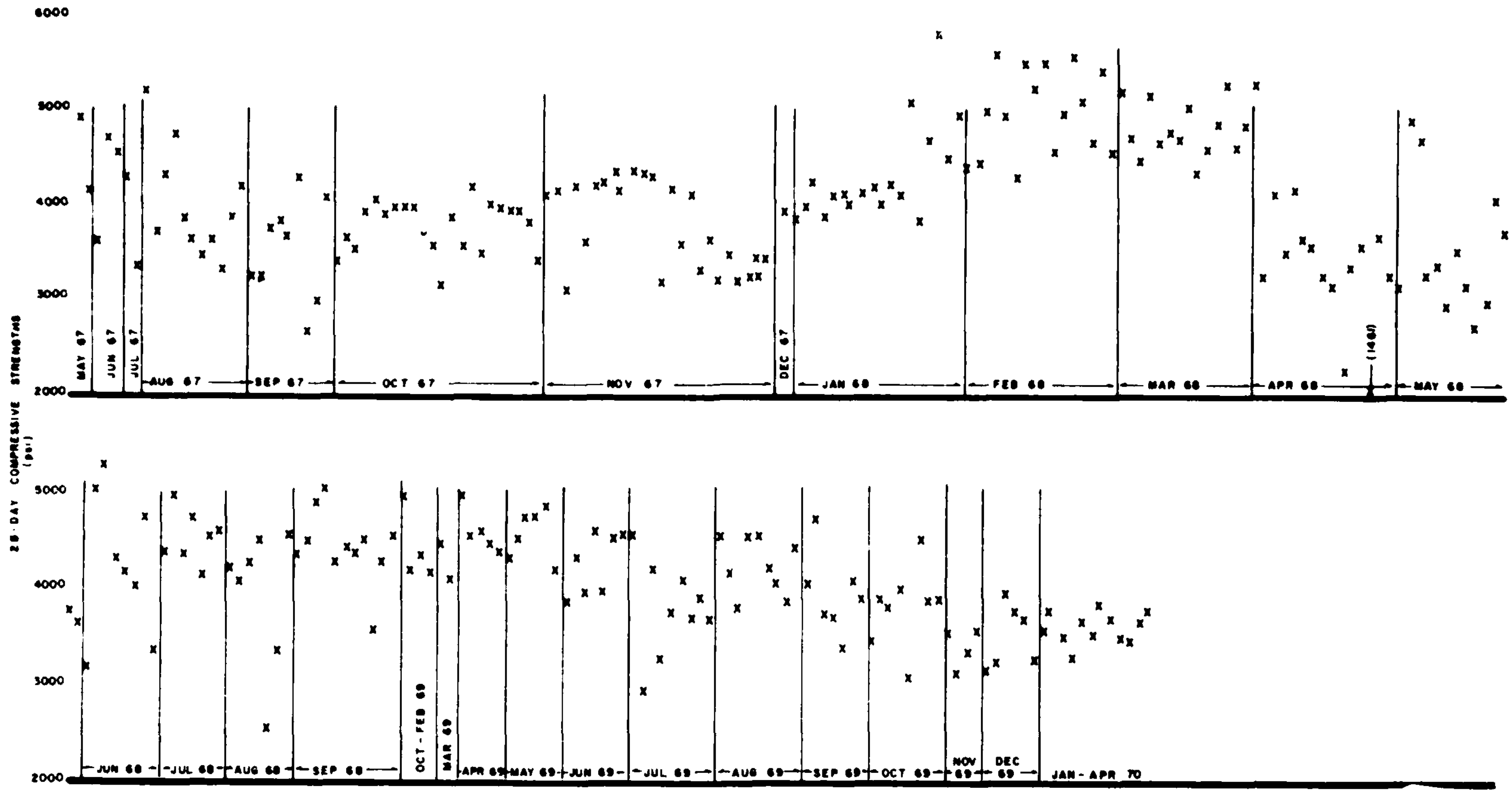

Figure 23. Graph of average daily values, WCCB building.

Table 7

Coral Concrete Salt Content Core Samples

Core Source	Spec.	Location	Depth	NaCl %
Saipan High Commissioner Residence				
Roof Spec No. 1#		Top	2 in.	.04
		Middle	2 in.	.05
		Bottom	2 in.	.03
Floor Spec No. 1#		Top	2 in.	.02
		Middle	2 in.	.01
		Bottom	2 in.	.01
	2#	Top	2 in.	.03
		Middle	2 in.	.01—
		Bottom	2 in.	.01—
	3#	Top	2 in.	.01
		Middle	2 in.	.01—
		Bottom	2 in.	.01—
Test Lab. Public W. Floor				
Floor Spec No. 1#		Top	2 in.	.07
		Middle	2 in.	.05
		Bottom	2 in.	.08
	2#	Top	2 in.	.06
		Middle	2 in.	.04
		Bottom	2 in.	.04
	3#	Top	2 in.	.05
		Middle	2 in.	.04
		Bottom	2 in.	.04
Japanese Hospital (abandoned) Spalled Chunk				.19
Isley Shelter - Floor				
Spec No. 1#		Top	2 in.	.04
		Middle	2 in.	.02
			2 in.	.02
			2 in.	.01—
		Bottom	2 in.	.01
	2#	Top	2 in.	.04
		Middle	2 in.	.02
		Bottom	2 in.	.02
Guam NAV STA Walkway Columns				
Spec No. 1#		Ext. Face (damaged)	2 in.	.09
		Middle	3 in.	.01
			3 in.	.01
		Ext. Face (opposite damaged)	2 in.	.02
	2#	Ext. Face (right angle from damaged face)	2 in.	.06
		Middle	3 in.	.02
			3 in.	.02
		Ext. Face (right angle from damaged face)	2 in.	.02
	3#	East Face	2 in.	.05
		Middle	3 in.	.01
			3 in.	.02
		West Face	2 in.	.01
	4#	South Face	2 in.	.03
		Middle	3 in.	.02
			3 in.	.02
		North Face	2 in.	.02
Piti Power Plant No. 1 Interior Shear Wall				
Basement Spec No. 1#		Face	2 in.	.10
		Middle	3 in.	.19
			3 in.	.36
		Face	2 in.	.60
	2#	Face	2 in.	.17
		Middle	3 in.	.18
			3 in.	.52
		Face	2 in.	1.00
	3#	Face	2 in.	.77
		Middle	4 in.	.61
		Face	2 in.	1.20
Piti Power Plant No. 2 Interior Shear Wall				
Basement Spec No. 1#		Face	2 in.	.03
		Middle	3 in.	.02
			3 in.	.01—
		Face	2 in.	.01—
	2#	Face	2 in.	.02
		Middle	3 in.	.02
			3 in.	.01
		Face	2 in.	.01—
	3#	Face	2 in.	.03
		Middle	3 in.	.02
			3 in.	.01
		Face	2 in.	.01—
OICC Test Lab Wall				
Spec No. 1#		Ext. Face	2 in.	.02
		Middle	2 in.	.01
		Int. Face	2 in.	.01
	2#	Ext. Face	2 in.	.03
		Middle	2 in.	.02
		Int. Face	2 in.	.01
	3#	Ext. Face	2 in.	.01
		Middle	2 in.	.01
		Int. Face	2 in.	.01
	4#	Ext. Face	2 in.	.02
		Middle	2 in.	.01
		Int. Face	2 in.	.02
SRF Calibration Bldg. Wall				
		S.E. Wall	2 in.	.01
		S. W. Wall	2 in.	.01
		S. W. Wall	2 in.	.01
		N. W. Wall	8 in.	.01
		N. E. Wall	2 in.	.02
Anderson AFB BOQ Bldg. 27001 Exterior Shear Wall				
Spec No. 1#		Face	2 in.	.02
		Middle	2 in.	.02
			2 in.	.02
			2 in.	.03
		Face	2 in.	.02
	2#	Face	2 in.	.02
		Middle	2 in.	.02
			2 in.	.01
			2 in.	.02
		Face	2 in.	.02
	3#	Face	2 in.	.01
		Middle	2 in.	.01
			2 in.	.01
			2 in.	.01
		Face	2 in.	.02
	4#	Ext. Face	2 in.	.03
		Middle	2 in.	.03
			2 in.	.02
			2 in.	.03
		Int. Face	2 in.	.02
Kwajalein Headquarters Bldg. No. 901 Walls				
1. East Face		Ext. Face	2 in.	.12
		Middle	2 in.	.09
			2 in.	.10
		Int. Face	2 in.	.10

Table 7 (cont'd.)

Core Source			NaCl %
2. North Face			
	Ext. Face	2 in.	.21
	Middle	2 in.	.17
		2 in.	.10
	Int. Face	2 in.	.09
3. West Face	Ext. Face	2 in.	.11
	Middle	2 in.	.06
		2 in.	.07
	Int. Face	2 in.	.07
4. South Face			
	Ext. Face	2 in.	.09
	Middle	2 in.	.10
Pacific B.Q Bldg. 704 Walkway			
1. 1st Deck	Top	2 in.	.09
	Middle	2 in.	.08
	Bottom	2 in.	.03
2. 2nd Deck	Top	2 in.	.24
	Middle	2 in.	.11
	Bottom	2 in.	.13

Core Source		NaCl %
Cold Storage Bldg. No. 701A Roof Overhang		
	Top 2 in.	.13
	Middle 2 in.	.15
	2 in.	.13
	Bottom 2 in.	.08
Cold Storage Bldg. No. 612 Roof Overhang		
1.	Top 2 in.	.02
	Middle 2 in.	.03
	2 in.	.02
	Bottom 2 in.	.02
2.	Top 2 in.	.02
	Middle 2 in.	.03
	2 in.	.02
	Bottom 2 in.	.02
Cargo Pier Floor New Section		
1.	Top 2 in.	.19
	Middle 4 in.	.12
	Bottom 2 in.	.10

Core Source			NaCl %
2.		Top 2 in.	.14
		Middle 2 in.	.11
		2 in.	.09
		Bottom 2 in.	.15
Floor Old Section			
1.		Top 2 in.	.94
		Middle 2 in.	.55
		2 in.	.25
		Bottom 2 in.	.32
2.	Top	2 in.	.75
	Middle	2 in.	.62
		2 in.	.45
	Bottom	2 in.	.46
Midway Spalled Concrete Samples			
BOQ Bldg. 4203			.65
Communication Bldg. 521			.07

Table 8

Aggregate Physical Properties

Source & Size	Specific Gravity (SSD)	Absorption	NaCl Concentration % (wt) ± .01%
Saipan + 5/8 in.	2.47	3.9	.01
− 5/8 in.	2.46	4.7	.01
Guam Quarry A 1 1/2 in.	2.38	5.1	.00
3/4 in.	2.34	5.9	.01
Fine	2.45	3.8	.01
Quarry B 1 1/2 in.	2.45	3.7	.00
Fine	2.51	2.7	.00
Kwajalein 3/4 in.	2.49	4.2	.02
Fine	2.53	2.5	.01
Midway Coarse	2.08	10.6	.14
Fine	[illegible]	5.2	.14

and sawing techniques were used to avoid leaching of salt from the test samples. Table 7 shows the results of the chloride test on the concrete slices. If the 0.2 percent salt concentration level is taken as the level below which steel will not corrode in a concrete environment, as indicated by the work of Klodt,[32] all concrete samples on the island of Saipan, with the exception of the sample from the Japanese hospital, had salt concentrations well below the threshold value.

With the exception of the samples obtained from Piti Power Plant No. 1, results of the chloride test for all samples from Guam were below the .2 percent threshold value. Surprisingly, even the samples obtained from the Naval station walkway columns and from Building 27001, Anderson AFB, were below the threshold level of salt concentration. Nevertheless it was noted in the field evaluation that concrete cover over the corroding reinforcing steel for both structures was less than 1 inch thick. Salt content values for the old Piti Power Plant (Plant No. 1) were well above the threshold value. The field evaluation showed significant corrosion of reinforcing steel and spalling of concrete.

Conditions at Kwajalein were considerably different. Nearly all buildings that were constructed during the 1950's had levels of salt concentration near or above .2 percent threshold level. Maintenance records showed that each of these buildings had required some structural maintenance. Newer facilities, such as the cold storage building No. 612, had levels of salt concentration far below the threshold value.

Since coring was not conducted at Midway salt content tests were limited to two samples of spalled concrete. One sample (Table 8) had a very high salt content and the other had a low salt content; both had spalled due to corroding reinforcing steel.

The salt concentration test on each 2-inch disk taken from the same core sample indicated that where exterior-interior wall surfaces were involved concentration gradients would normally occur. The exterior 2-inch disk had higher salt contents than the interior or middle disks. It was also noted that some exterior faces had higher levels of salt than others. These faces were often perpendicular to the direction of the prevailing wind.

5 DISCUSSION AND ANALYSIS: FIELD EVALUATION, DOCUMENTED INFORMATION, AND LABORATORY TEST

This investigation concludes that coral has been used successfully as an aggregate for concrete in vertical construction. Construction techniques currently being used at Guam, Siapan, and Kwajalein, in the production of coral aggregate and coral concrete, are similar to conventional aggregate and concrete techniques. The remoteness of the islands from equipment and spare parts, the limited and fluctuating construction volume, and the location of the aggregate source (Kwajalein only) influenced the type, age, and condition of construction equipment used. The field evaluation revealed that the only significant type of deterioration in coral concrete structures was the cracking and spalling concrete associated with corroding reinforcing steel. The severity of the corrosion-spalling problem varied considerably, but on each of the islands at least one structure had deteriorated to the point where its integrity had been affected.

Information obtained from a review of available records disclosed that specifications currently being used for production of coral aggregate and coral concrete on the islands of Guam, Saipan, and Kwajalein, are similar to specifications for production of conventional aggregate and concrete. Other information obtained from the records indicated that until the mid-1950's much of the coral concrete placed was unsatisfactory. Primary reasons were the use of low quality coral, haphazard grading, poor uniformity of concrete, and inferior placing and curing of concrete. Coral concrete produced after the mid-1950's was usually more uniform in quality. However, in instances where salt or brackish mix water was used, rapid corrosion of embedded conduit and reinforcing steel was observed together with concrete cracking and spalling.

Laboratory analysis of the salt content in the coral concrete samples showed that where levels were

[32] D. L. Klodt, "A Study of Prestressing Steel-Effect of Stress, Metallurgical Structure and Environment," *Proceedings of National Association of Corrosion Engineers, 24th Conference* (1969).

high, the related structures had corroding reinforcing steel. In some cases, corrosion was observed where salt levels were very low, but in these same cases, the cover over the reinforcing steel was very shallow when compared to recommended ACI standards for minimum cover of reinforcing steel.

6 CORROSION OF REINFORCING STEEL IN CORAL CONCRETE

Corrosion Mechanisms and Influencing Parameters. The corrosion of steel embedded in concrete is the only major existing deficiency of coral concrete. Steel corrosion in a concrete environment, whether coral or conventional aggregate, is an electro-chemical, oxidation-reduction reaction. The oxidation or anodic half of the reaction is:

$$Fe \rightarrow Fe^{++} + 2e^- \qquad [Eq\ 1]$$

and the reduction or cathodic reaction is:

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-. \qquad [Eq\ 2]$$

The oxidation-reduction reactions must be balanced for corrosion to progress. Thus, the rate of oxygen transport or diffusion through the free water in the concrete to the metal surface can control the reaction rate.

Alkalinity of the free water (electrolyte) in concrete is also important. The pH of free water in a concrete environment is normally 12.8. At this pH steel is normally passive and corrosion is inhibited. But if a minor amount of chloride ions are present in the electrolyte, the passivity of the steel is destroyed and corrosion can occur. Sodium chloride (salt) concentrations as low as 0.2 percent will significantly affect the passivation, and with concentrations in excess of 0.5 percent NaCl, passivation is almost impossible to achieve.

Corrosion Protection. The above indicates that two conditions must exist before steel will corrode in concrete: (1) sufficient chloride ions present in the electrolyte to depassivate the steel, and (2) an adequate rate of oxygen transport in the electrolyte through the concrete to the metal surface. When such conditions exist, as was often the case with many of the existing coral concrete structures, corrosion and concrete spalling occur.

New construction techniques to inhibit corrosion can be specified. Salt concentration in the materials should be held to a minimum. Consequently, brackish or sea water should not be used as mix water, nor should contaminated aggregate be used with salt. The amount of concrete cover over reinforcing steel should be increased to a minimum of 3 inches or more in areas of exposure. The use of high quality-low permeability concrete will also assist in retarding the rate of oxygen and chloride ion transport to the metal surface. In a few instances cathodic protection has been used to protect reinforcing steel, but cathodic protection has been found to be uneconomical. Sodium nitrate inhibitors have also been used, but to be effective they must be added in excessive amounts. According to recent studies, galvanized coatings on reinforcing steel will inhibit corrosion for a short time. The results of initial laboratory tests also reveal that epoxy coatings on reinforcing steel may provide adequate long-term corrosion protection. Field evaluation of epoxy coatings are currently being initiated by various state highway departments.[33]

Once active corrosion of the reinforcement has started in existing structures, there is no satisfactory technique to stop further corrosion. Many concrete surface coatings and impregnation materials have been tested, but most are ineffective in retarding moisture (dissolved oxygen) migration through the concrete over a reasonable length of time. Some of the more common coatings that have been used are paints, coal tars, cut-back asphalts, and asphalt emulsions.

7 SUMMARY

Conclusions. The following is a list of conclusions that were drawn from this investigation on the use of coral as an aggregate for portland cement concrete vertical construction and structures.

1. Coral has been used successfully as an aggregate for portland cement concrete.

[33] Gene Dallaire, "Designing Bridge Decks That Won't Deteriorate," *Civil Engineering*, Vol 43, No. 8 (ASCE, August 1973), pp 43-48.

2. Quality concrete can be produced with coral aggregate if the quality of the coral is uniform and the amount sufficient to meet conventional aggregate specifications.

3. If salt-laden coral, sea water or brackish mix water are used in the production of concrete, rapid corrosion of embedded conduit and reinforcing steel is likely to occur.

4. No satisfactory techniques have been developed for inhibiting corrosion of embedded steel in concrete once corrosion has begun.

Recommendations. When coral is used as an aggregate for concrete in which reinforcing steel or conduit is to be embedded, all salts should be leached from the coral, and the use of sea or brackish mix water prohibited. Minimum concrete cover over reinforcing steel should be 2½ to 3 inches of high-quality, low-permeability concrete. This will result in a low maintenance, long lasting structure reasonably free of steel corrosion.

It is further recommended that studies be initiated to develop techniques to inhibit corrosion of embedded steel once active corrosion has begun. Results of on-going field tests on bridge decks will determine the feasibility of using epoxy coatings on reinforcing steel. If results are favorable, use of epoxy-coated reinforcing steel should be considered when salt contamination of concrete cannot be avoided.

APPENDIX A:

AGENCIES AND PERSONNEL INVOLVED IN STUDY (Other than CERL)

Officer in Charge of Construction,
Naval Facilities Engineering Command, Contracts
Marianas, Guam
Mr. B. M. Scruggs, Materials Branch, Manager
Mr. O. M. David, Materials Testing Branch
Mr. D. C. Camacho, Materials Branch

Trust Territory of Pacific Islands (Saipan)
Mr. G. W. Bradley, Director of Public Works
Mr. P. B. Cristi, Test Laboratory Engineer

Corps of Engineers Pacific Ocean Division, Honolulu
Mr. J. S. Ravina, Chief, Foundation Materials
and Survey Branch
Mr. J. Roy, Geologist, Foundation Materials
and Survey Branch
Mr. Cook, Resident Engineer, Kwajalein
Mr. J. Faust, Deputy Resident Engineer, Kwajalein

Navy OICC Mid Pacific, Honolulu
Mr. E. Ralph, Director, Construction Division
Mr. W. Horne, Architectural Branch, Engineering
Division
LCDR Farbarik, Director Public Works
Department, Naval Station
Chief Petty Officer E. A. R. Pardiness, Public
Works Department, Midway Naval Station

Naval Civil Engineering Laboratory
Mr. W. R. Lorman

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GLOSSARY[34]

Limestone: A sedimentary deposit the origin of which is classified petrologically as organic residue; the deposition may be biochemical or biomechanical. Though consisting predominantly of calcium carbonate, these deposits normally contain some magnesium carbonate.

Coralline limestone: A biochemical limestone consisting of coral fragments and other calcareous organic detritus all intermixed and consolidated with heterogeneous calcareous sand and marine sediment. The calcium carbonate originally is crystallized in the form of the mineral aragonite which, being unstable, is altered into the more stable mineral calcite. Corals (polyps), calcareous algae, foraminifera, shellfish (mollusca), and miscellaneous aquatic crustaceans are the principal organisms involved in the formation of this material. The porosity of coralline limestone varies with the geological derivation and is related to volume contraction associated with calcite in solution during production of magnesium carbonate in the presence of sea water.

Coral: The following terms denote the vernacular associated with the multitude of forms in which coral occurs: brain, mushroom, disc, leaf, finger, staghorn, and ledge. In the Pacific Ocean area the most common and perhaps the most important genus of reef-building corals is acropora.

Reef coral: A compact composite of coralline limestone, cellular coral, and vesicular coral rock; found in the form of existent barrier or fringing reefs; staghorn coral may be found interspersed or intergrown therewith. Though lithologically a massive material, reef coral normally is more porous than quarry coral. Particle shape of crushed reef coral varies; generally it is all angular, occasionally the coarse fractions may be predominantly finger, and occasionally the majority of fine fractions may be subround. The surface texture usually is moderately rough but sometimes may be nearly smooth. The typical color is white or nearly white, whereas coral beach sand (which usually originates from the reef) tends toward buff or tan color.

Ledge coral: Ledge coral (sometimes known as coral beach rock) is found at locations where natural conditions have caused calcium carbonate deposition in the form of slabs which cover the ocean bottom along the shore line. Calcite in solution assists in filling the interstices of the rock, the initial porosity of which results from loose intergrowth of shell-bearing marine organisms.

Lagoon coral: Similar to reef coral except that cemented fragments normally are absent. It is usually found in lagoon bottoms mixed with coral sand (and sometimes intermixed with clays) and occasionally mixed with sands of volcanic origin. Hydraulic dredging tends to pulverize the softer coral particles which, together with any clays present, are discarded while in solution; the remaining coralline materials are pumped to shore as the principal product of the dredging operation. Lagoon coral so dredged is a fairly-graded mixture of particles ranging from cobble size to fine sand size, but it is definitely an inferior coral aggregate although not as unsatisfactory as cascajo.

Cascajo: This Spanish term peculiar to Guam where the material is most abundant, signifies "gravelly coral" and refers to lagoon sediment and to talus and detritus of eroded coral reefs elevated previously as the result of seismic disturbances. The petrographical structure of cascajo does not justify economy in concrete construction because the material exhibits large amounts of soft calcareous particles, ranging from silt to small cobbles, and possesses no appreciable resistance to abrasion; it is notorious for imparting poor durability characteristics to concrete.

Coral beach sand: Disintegrated reef coral and fragments of marine shells. Color usually is buff; particle shape is predominantly subangular; and surface texture is nearly smooth in most cases. Coral beach sands consist of varying proportions of coralline limestone, cellular coral, and vesicular coral rock, in addition to the calcareous marine-shell fragments interspersed therewith.

[34]William R. Lorman, *Coral and Coral Concrete*, TR 068 (USN CEL, 1960), pp 37-40.

Bank-run coral: Loose deposits of coral conglomerate cemented with calcium carbonate; normally composed of cellular coral, compact coral rock, and a conglomeration of partly rounded coralline limestone grains. The coarse portions may be somewhat friable; the fine portions occasionally may show evidence of silt, which is easily removed by washing. Particle shape is predominantly subangular; surface texture varies from rough to moderately rough, dependent respectively upon whether coarse or fine fractions are under consideration; and the range in color is restricted to white or nearly so. The amount of fines frequently is excessive; finger coral often is interspersed in quantities that may range from minor to major proportions.

Quarry coral: Reef material geologically older than that in existent barrier or fringing reefs and found in the form of ancient reefs elevated above sea level. The composition is finely crystalline limestone containing fossilized coral, or stated otherwise, coralline limestone. Crushed particles usually range from angular to subangular in shape, color normally is nearly white, and predominant surface texture is either rough or moderately rough. Crusher-run sand manufactured from quarry coral usually is deficient in the PLUS No. 50 MINUS No. 30 sizes.

Finger coral: A remnant of staghorn or similar branching coral. These fragmentary pieces, the shape of which resembles a human finger, are relatively fragile, lightweight, and highly porous.

Rock flour: MINUS No. 200 material created by attrition and breakage of coral aggregate particles incident to mechanical movement during processing, stockpiling, removal from storage, and batching at the mixer.

"Dead coral" and "live coral": It is undesirable to use the terms "dead" and "live" when referring to coral aggregates. "Dead coral" is a deceptive term that too often has been used to describe coralline material that has been dried under the sun for a long time. The term "live coral" likewise has been fallaciously used to describe coralline material removed from the sea so recently that it was yet saturated with sea water (not to be confused with "live" in the sense that the organisms still were alive). The term "live coral" or "living coral" should be used only in reference to the skeleton of the live polyps or algae; such live coral never is used directly as concrete aggregate in view of the excessive organic content present. Use the term "fresh coral" for the saturated type recently excavated from the reef under water; use the term "dried coral" when referring to coralline material that is in the relatively dry state (bank-run and quarry corals).

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